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RESEARCH MEMORANDUM

BLOW-OUT VELOCITIES OF SEVERAL SLURRY AND LIQUID FUELS IN A $1\frac{7}{8}$-INCH-DIAMETER COMBUSTOR

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BLOW-OUT VELOCITIES OF SEVERAL SLURRY AND LIQUID FUELS IN A $1\frac{7}{8}$-INCH-DIAMETER COMBUSTOR

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SUMMARY

Blow-out velocities of several slurry and liquid fuels were determined in a $1\frac{7}{8}$-inch-diameter combustor. A slurry produced by quenching vaporized magnesium with JP-4 fuel demonstrated a reactivity greater than that of any slurry previously evaluated in this combustor.

Neohexane and a slurry containing 60 percent of 18-micron magnesium in neohexane had the same blow-out limits. However, a slurry containing 60 percent of the same 18-micron magnesium powder in propylene oxide yielded blow-out velocities substantially greater than those for the propylene oxide fuel.

A slurry of 50 percent, 0.5-micron boron in JP-5 fuel gave blow-out velocities greater than those of JP-4 fuel at high equivalence ratios.

INTRODUCTION

In an effort to increase aircraft range and jet-engine thrust, investigations were conducted at the NACA Lewis laboratory to evaluate the applicability of metal-hydrocarbon slurries as fuels for ram-jet engines and afterburners. This evaluation of slurries has included both experimental and analytical studies as described in references 1 to 8.

From results of experimental studies of stability limits and combustion efficiency, it has been concluded (refs. 3 to 5) that magnesium powder of 1-micron average particle diameter or less is perhaps the most satisfactory metal slurry component for improving engine thrust. However, large particle-size magnesium (approximately 15 microns in average diameter) is still of interest because of availability, handling ease, safety, and fuel density characteristics, if efficient combustion can be obtained. Since the reactivity of the slurry depends on the individual reactivities of the components, more efficient combustion of the metallic portion would be promoted by a more reactive liquid component.

In addition to the interest in magnesium for greater engine thrust, attention has been given to the use of boron-hydrocarbon slurries to provide greater flight range. Unfortunately, however, the high theoretical heating value per unit weight of boron slurries has not yet been attained because of inefficient combustion relative to JP-4 fuel (ref. 9). For this reason, reactivities of slurries made with higher purity, smaller particle-size boron are being investigated.

The specific object of this investigation was to compare the reactivities of several magnesium slurries and their vehicles. The slurries differ in terms of magnesium particle size and vehicle reactivity. Blow-out velocities in a $1\frac{7}{8}$-inch-diameter ram-jet combustor, as functions of equivalence ratio, were determined for the following slurry and liquid fuels: a slurry produced by quenching magnesium vapor with JP-4 fuel (ref. 10); a slurry containing 18-micron magnesium (produced by gas atomization) in neohexane; a slurry containing 18-micron magnesium in the more reactive vehicle, propylene oxide; neohexane; propylene oxide; and JP-4 fuel. In addition, the blow-out velocities of a slurry containing 0.5-micron boron in JP-5 fuel were determined.

APPARATUS AND PROCEDURE

The combustor, exhaust, and fuel system are shown in figure 1. Details of the combustor are illustrated in figure 2.

This apparatus and the operational procedures have been discussed in a previous report of investigations of blow-out velocities of various fuels in the $1\frac{7}{8}$-inch-diameter combustor (ref. 5). Some refinements of the air atomizing fuel nozzle were effected previous to the work reported herein. The primary dimensions of the nozzle were maintained; however, the design changes caused definite shifts in reference curves for blow-out velocities of JP-4 and propylene oxide fuels.

For the determination of the blow-out limits, the atomizing air flow was held constant, a steady fuel flow was maintained, and the main air flow was set low enough for ignition of the fuel-air mixture and was then gradually increased until flame failure occurred.

The velocity at blow-out was computed from the air flow at a reference area corresponding to the combustor-chamber inlet ($1\frac{7}{8}$-in. diam) with atmospheric pressure and temperature assumed. Slurry-flow rates were determined by multiplying the measured flow of JP-4 fuel used to displace the slurry by the ratio of the densities of slurry and JP-4 fuel. The liquid fuels were pressurized with helium and their flow rates were measured directly.

Descriptions of the properties of the fuels used in this investigation are given in table I.

RESULTS AND DISCUSSION

Limitations of results. - The $1\frac{7}{8}$-inch-diameter combustor used in this investigation is a fixed configuration. It is limited to conditions (such as, temperature, pressure, velocity, fuel atomization, mixing, and recirculation) which represent only a small portion of the range for practical jet-engine operation. The small-scale combustor magnifies effects which are functions of wall surface per unit volume of combustor. For example, radiation from the wall at high combustion temperatures is an important factor in the case of fuels containing solid particles. This influence should contribute to the inability of reactive magnesium slurries to "blow out" at higher fuel rates.

In any event, absolute comparisons of over-all potentials of fuels, or numerical extrapolations of performance to larger combustors or jet engines cannot be supported quantitatively by blow-out velocities determined in the small-scale combustor. Further, relative comparisons of blow-out velocities for fuels of widely differing physical and/or chemical properties would not be as accurate as comparisons of fuels with similar components, concentrations, and properties.

Blow-out velocities of three magnesium slurries and three liquid fuels. - A comparison of the blow-out velocities of three magnesium slurries and three liquid fuels is shown in figure 3. Data for JP-4 and propylene oxide fuels are presented because refinements in the fuel nozzle of the $1\frac{7}{8}$-inch-diameter combustor caused significant changes in these reference curves relative to those presented in reference 5.

The blow-out velocities of the slurry produced by quenching vaporized magnesium in JP-4 fuel represent the maximum reactivity demonstrated by any fuel in this combustor. The blow-out velocity of the slurry produced by quenching vaporized magnesium in JP-4 fuel increased from 57 feet per second to over 240 feet per second, while equivalence ratio decreased from 0.43 to 0.31. Reference 5 shows that the blow-out velocities of a slurry containing 50 percent 1.5 micron magnesium (83 percent purity) increase along the line of equivalence ratio of 0.46.

The reduction in equivalence ratio with increasing blow-out velocity observed with the vaporized magnesium slurry can be caused by changes in local operating conditions. The more reactive fuels effect a large gas-stream temperature rise within the combustion chamber. This rise, in turn, results in an increased momentum pressure drop from the combustor

inlet to the exit, which is open to atmospheric pressure. The higher combustor-inlet pressure will promote more efficient burning, which will cause a greater temperature ratio with a correspondingly larger pressure drop, and thereby cause the self-induced situation to progress for highly reactive fuels.

Since the blow-out velocity is computed at the measured air flow assuming atmospheric pressure and temperature at the inlet of the combustion chamber, the actual velocity can be considerably different from the calculated value at blow out. However, the relative trends of the defined blow-out velocity-equivalence ratio relations for reactive fuels still provide bases for a comparison of reactivity.

The blow-out velocities of neohexane fuel and the slurry containing 60 percent 18-micron magnesium in neohexane lie essentially on the same curve. This effect was characteristic of magnesium-JP-4 fuel slurries when large particle sizes were used (unpublished data). However, variation of particle-size distribution for a given average particle size can influence the slurry blow-out velocities. Since it appears that magnesium burns in the vapor phase (ref. 11) and vaporization rate is a function of particle surface (ref. 12), the important particle-size parameter for reactivity of magnesium slurries is surface area per unit weight (or volume).

A slurry containing 60 percent 18-micron magnesium in propylene oxide was made from the same magnesium powder used for the magnesium-neohexane slurry. Relative to the curves for propylene oxide and the magnesium-neohexane slurry, the blow-out velocity curve shown in figure 3 for the magnesium-propylene oxide slurry reveals a marked synergistic effect. A maximum blow-out velocity of 134 feet per second was reached at an equivalence ratio of 1.9 for the propylene oxide fuel. In the case of the magnesium-propylene oxide slurry, a blow-out velocity of 177 feet per second was measured at an equivalence ratio of 0.95. The blow-out velocity trend at this point does not indicate an immediate approach to a maximum.

This effect may result from rapid evaporation and efficient burning of the propylene oxide, exposing the magnesium particles to higher temperatures earlier in the combustion process. However, the availability of relatively reactive oxygen in the three-membered ring structure of propylene oxide could provide increased potential for reaction of the metallic portion of the slurry.

Whatever the mechanism, it appears that further investigation of slurries involving combinations of metals and partial auto-oxidizing fuels is warranted.

Some fuel properties of interest in addition to the reactivity of a fuel are stoichiometric fuel-air ratio, specific gravity, and heats of combustion. These values for JP-4 fuel and for slurries of 60 percent magnesium in propylene oxide and in JP-4 fuel are given in the following table:

Fuel	Stoichiometric fuel-air ratio	Specific gravity, g/cc	Heats of combustion		
			Btu/lb fuel	Btu/cu ft fuel	Btu/lb air at stoichiometric
JP-4	0.068	0.76	18,700	886,000	1270
60 Percent Mg in propylene oxide	.183	1.21	11,600	876,000	2120
60 Percent Mg in JP-4	.132	1.14	13,900	989,000	1840

In practical application, the greater reactivities of the slurries can produce higher combustion efficiencies and wider stability limits relative to those of the JP-4 fuel. This effect would tend to shift the heats of combustion toward values more favorable to the slurries. It is also possible to attain levels of heat liberation per pound of air with slurries that are impossible with the JP-4 fuel.

<u>Blow-out velocities of a 0.5-micron boron - JP-5 slurry</u>. - Blow-out velocities for a slurry of 50 percent 0.5-micron boron in JP-5 fuel are given in figure 4. The reference JP-4 fuel curve has been included for comparison. The blow-out velocity curve for the boron - JP-5 fuel slurry extends above that of the JP-4 fuel at high equivalence ratios. This indicates improved reactivity by comparison with previously investigated boron slurries (ref. 5). References 5 to 7 predict that maximum blow-out velocities for JP-4 and JP-5 fuels should not be measurably different.

CONCLUDING REMARKS

The blow-out velocity trends of a slurry produced by quenching vaporized magnesium with JP-4 indicate a reactivity greater than any slurry that has been evaluated previously in the $1\frac{7}{8}$-inch-diameter combustor. This result agrees with previous studies that predict greater reactivity with decreasing magnesium particle size in slurries.

The blow-out velocity limits of the neohexane fuel and a slurry of 18-micron magnesium in neohexane were the same. A slurry containing the same 18-micron magnesium powder in a propylene oxide gave a blow-out velocity curve considerably higher than the one for propylene oxide fuel.

These results suggest the use of reactive liquid components (with groups that can act as oxidizing agents) to improve the performance of slurries made with less reactive metallic components.

It should be noted that no study of the storage stability of the propylene oxide-magnesium slurry was made. Certainly, the use of anhydrous propylene oxide would be mandatory in the production of such a slurry. Any attempt to produce a similar slurry with small particle-size, reactive magnesium should be made with extreme caution.

The application of a more reactive liquid vehicle to boron slurries may offer a means of improving their reactivity. While the blow-out velocities of the slurry containing 0.5-micron boron in JP-5 fuel were greater than those of the JP-4 fuel at higher equivalence ratios, a means of increasing stability limits and combustion efficiencies of such slurries certainly is desirable.

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National Advisory Committee for Aeronautics
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TABLE I. - FUELS AND FUEL PROPERTIES

Fuel	Powder particle size, microns	Powder purity, percent by weight	Remarks
MIL-F-5624B	----	----	JP-4 Grade
Propylene oxide	----	----	Technical grade
Neohexane	----	----	Technical grade
60 Percent magnesium in neohexane	[a]18	94	No additive
60 Percent magnesium in propylene oxide	[a]18	94	No additive
50 Percent boron in JP-5 fuel[c]	[a]0.5	88.7	1.5 Percent G-672[d]
50 Percent vaporized magnesium in JP-4 fuel	[b]1	81	2.3 Percent G-672[d]

[a]Average particle-size designations were determined by Fisher Sub-Sieve Sizer (an air permeability method).

[b]Microscopic examination showed most particles to be less than 1 micron in diameter.

[c]The properties of the fuel designated as JP-5 conform to specification MIL-F-5624B, ammendment 1.

[d]G-672 is a commercially surface active agent containing glycerol sorbitan laurate.

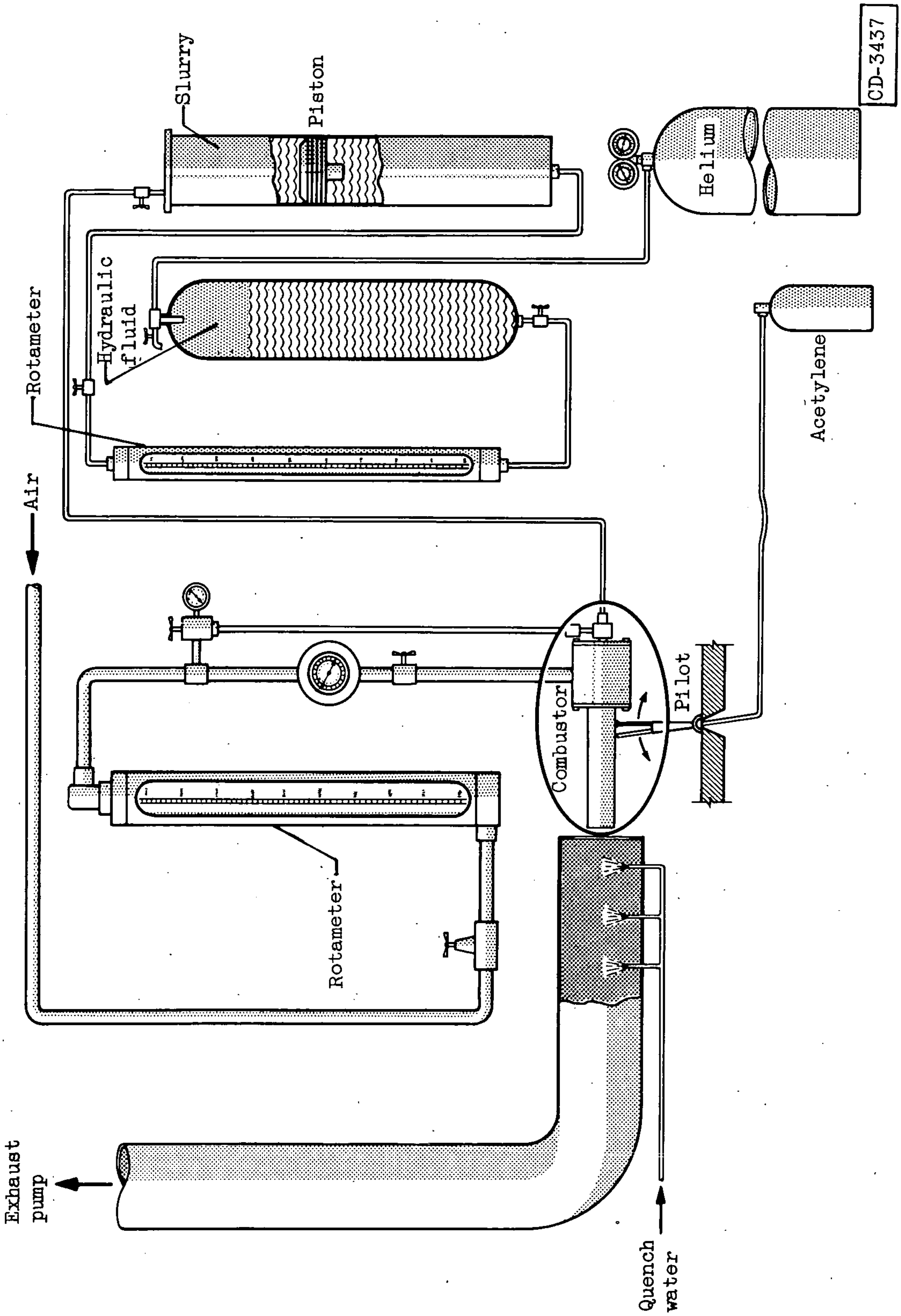

Figure 1. - Test installation used to determine blow-out velocities of fuels.

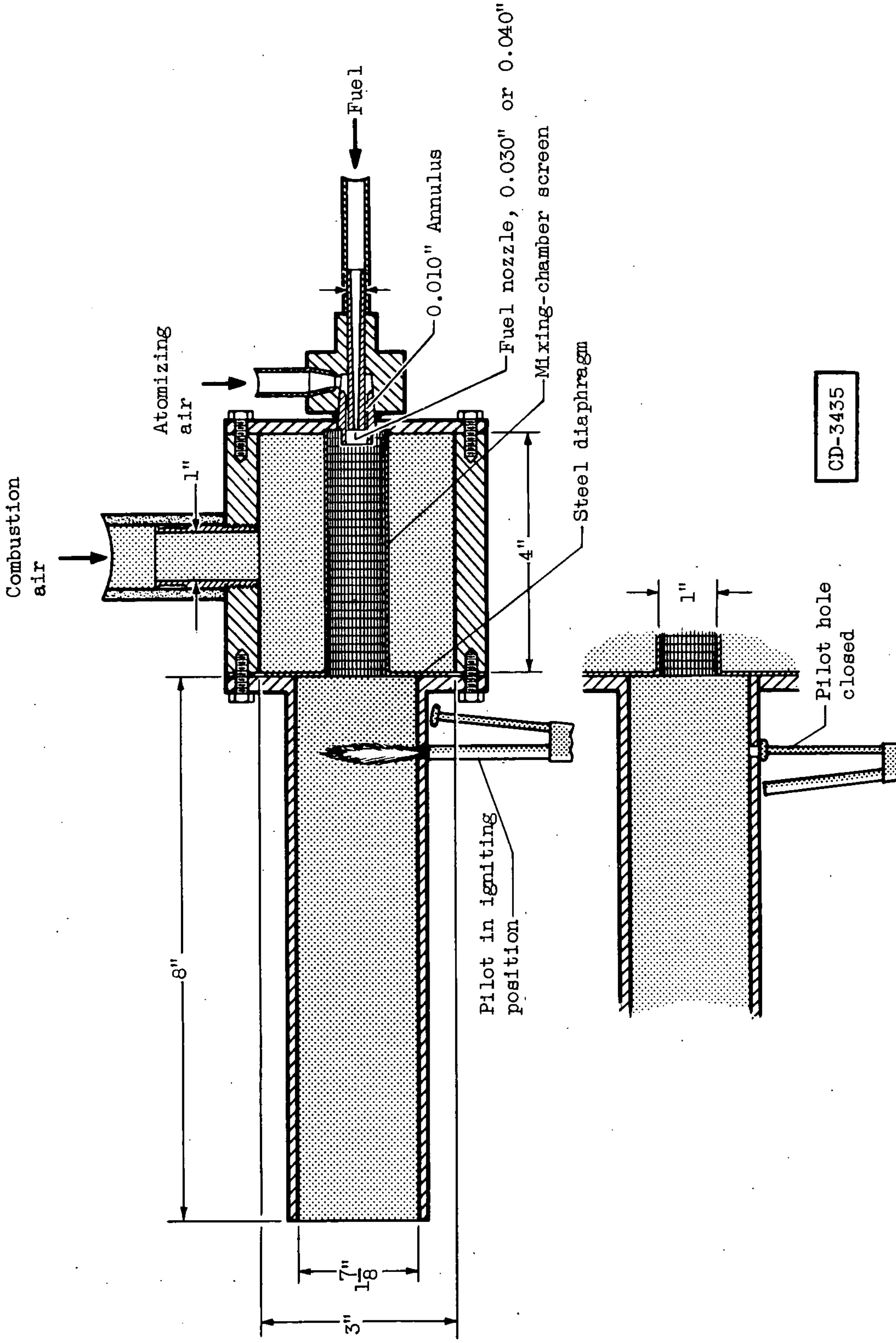

Figure 2. - Combustor, pilot, and mixing chamber.

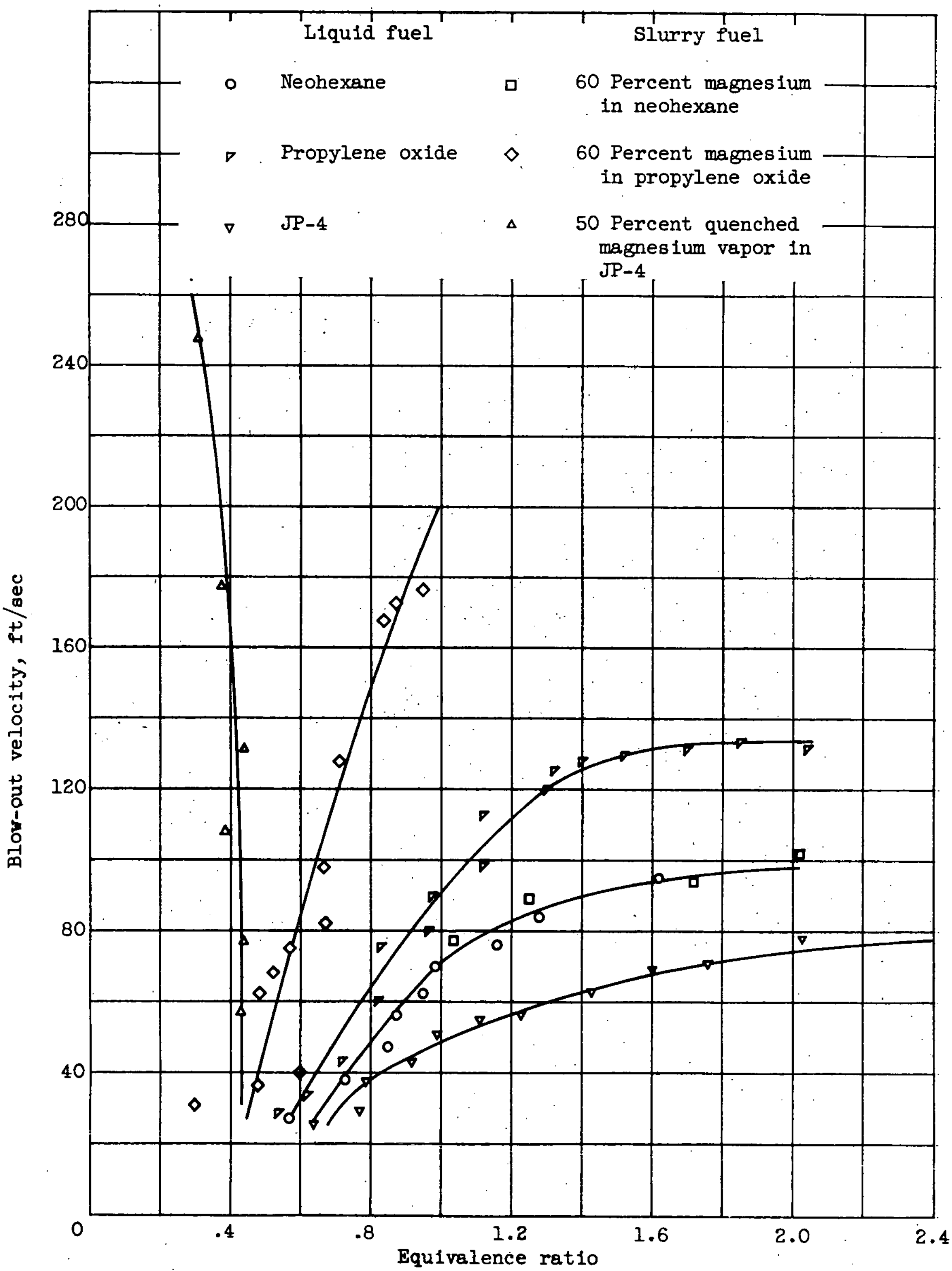

Figure 3. - Blow-out velocities of three magnesium slurries and three liquid fuels.

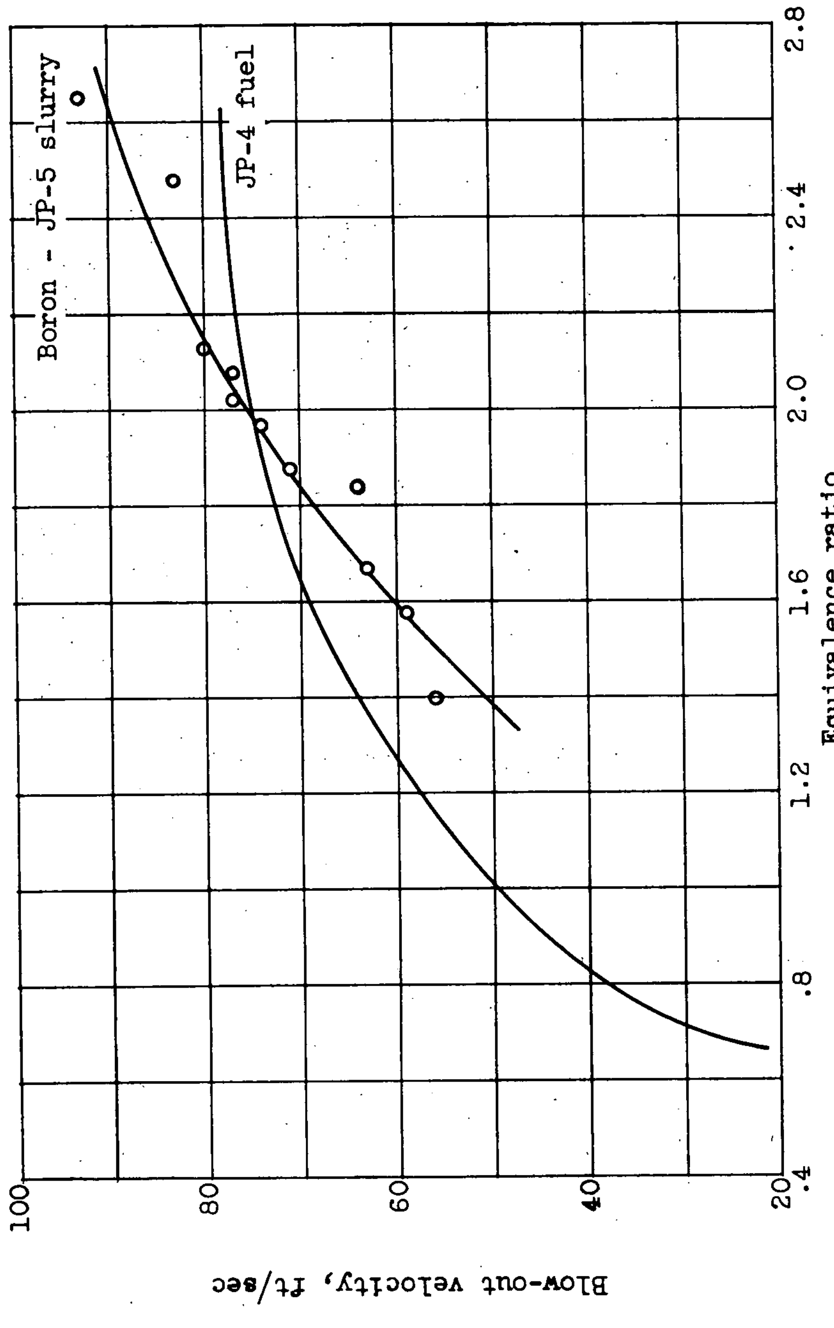

Figure 4. - Blow-out velocities of slurry containing 50 percent boron in JP-5 fuel; average particle size, 0.5 micron.

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